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Una visión general de aplicaciones biomédicas de los piezoeléctricos
An overview of biomedical applications of piezoelectrics

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Resumen

Los dispositivos piezoeléctricos han surgido como herramientas versátiles en biomedicina, ofreciendo soluciones innovadoras para diversas aplicaciones clínicas y de investigación. Este artículo examina algunos de los avances más recientes en el uso de dispositivos piezoeléctricos en biomedicina, destacando sus aplicaciones en diagnóstico, terapia y monitorización biomédica. El análisis se centra en los avances más relevantes en la fabricación de dispositivos piezoeléctricos con propiedades mejoradas, incluyendo la miniaturización, la integración multifuncional y la optimización de la eficiencia energética. Se analizan las tecnologías emergentes, como los transductores piezoeléctricos implantables para la monitorización continua de parámetros fisiológicos, los dispositivos de ultrasonidos de alta resolución para el diagnóstico por imagen y las plataformas de terapia de ultrasonidos focalizados de alta intensidad para el tratamiento no invasivo de enfermedades. Además, se abordan los retos actuales y las futuras líneas de investigación en este campo, como la mejora de la biocompatibilidad de los materiales piezoeléctricos, la optimización de la resolución y la profundidad de penetración en la obtención de imágenes por ultrasonidos, y la exploración de nuevas aplicaciones en áreas como la ingeniería de tejidos y la estimulación en órganos periféricos. En conjunto, esta revisión ofrece una panorámica completa de los avances más recientes en dispositivos piezoeléctricos aplicados a la biomedicina. Destaca su potencial para transformar la práctica clínica y ofrecer nuevas oportunidades en la investigación biomédica.

Palabras Clave: Piezoeléctrico, Biomédico, Salud, Rehabilitación, Polímeros.

Abstract

Piezoelectric devices have emerged as versatile tools in biomedicine, offering innovative solutions for various clinical and research applications. This review article examines the most recent advances in using piezoelectric devices in biomedicine, highlighting their applications in diagnostics, therapy, and biomedical monitoring. The analysis focuses on some of the most relevant developments in the fabrication of piezoelectric devices with improved properties, including miniaturization, multifunctional integration, and optimization of energy efficiency. Emerging technologies are discussed, such as implantable piezoelectric transducers for continuous monitoring of physiological parameters, high-resolution ultrasound devices for diagnostic imaging, and high-intensity focused ultrasound therapy platforms for non-invasive disease treatment. In addition, current challenges and future research directions in the field are addressed, including improving the biocompatibility of piezoelectric materials, optimizing the resolution and depth of penetration in ultrasound imaging, and exploring new applications in areas such as tissue engineering and stimulation of peripheral organs. This review provides a comprehensive overview of the most recent advances in piezoelectric devices applied to biomedicine. It highlights their potential to transform clinical practice and provide new opportunities in biomedical research.

Keywords: Piezoelectric, Biomedical, Healthcare, Rehabilitation, Polymers.

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1. Introducción

Biomedical engineering aims to enhance human health by integrating engineering, medicine, and biological sciences. Biomedical research topics encompass a wide range, from tissue engineering and surgical devices to medical imaging and orthopedic implants. On the other hand, the sensor technology to accomplish biomedical goals is also vast. Piezoelectric materials are used in several aspects of the aforementioned biomedical research; those materials find several applications in the biomedical field, ranging from scaffolds to in vivo sensors. Piezoelectric materials are the option of choice in the biomedical field because of their advantages, such as power generators, signal conversion, sensitivity, real-time monitoring, and continuous monitoring (Ghosh, 2023; Zhang et al., 2024; Zhou et al., 2020).

Briefly described, piezoelectricity can be defined as an electromechanical property present in various crystals and polymers, natural and artificial, which allows them to generate an electric charge when subjected to deformation. As shown in Fig. 1, a finger presses on a piezoelectric transducer, thus generating a potential difference (ΔV) between points V_A and V_B. This charge is directly proportional to the vectorial product of the applied mechanical stress times the piezoelectric constant; the same occurs reversely, i.e., it is possible to generate a mechanical deformation, which will be proportional to the electric field applied to the material. (Jaffe, 1971).

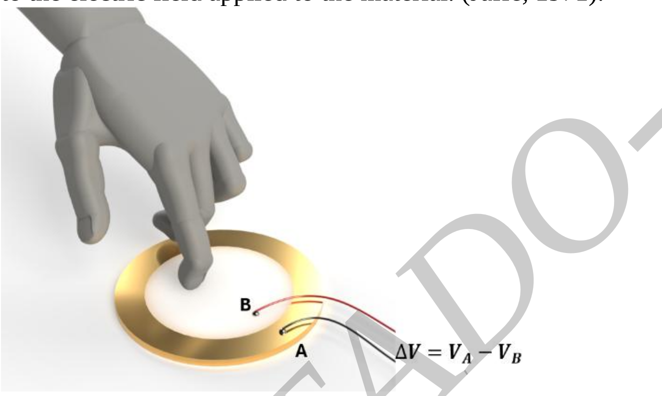

Figure 1: External mechanical perturbation generates a potential difference.

This deformation is almost negligible compared to the piezoelectric size, and because of this, it is possible to use them in precision instruments (Shrout et al., 1982). Because piezoelectric materials have the converse effect, they can be used as sensors or actuators. When operating as an actuator, a piezoelectric is a transducer capable of converting electrical energy into mechanical deformation. As a sensor, the property of the transducer that allows electrical energy to be generated when a mechanical disturbance occurs can be used to interpret these physical events as signals and process, collect, and display information from them (Fu et al., 2012).

Various materials are suitable for manufacturing this wide range of piezoelectric actuators and sensors, depending on the device's use. These materials can be divided into naturally occurring in our environment and those processed synthetically. Thus, the categorization depends on several factors, such as their materials, construction, and principle of operation. However, a general classification can be made, as shown in Fig. 2.

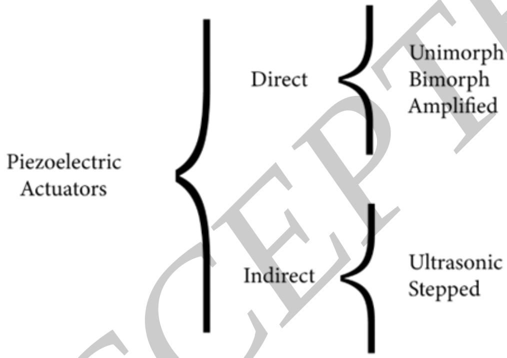

Figure 2: Classification of piezoelectric actuators

Piezoelectric actuators can be divided by their operation into direct and indirect. The main feature of direct actuators is that they exploit the piezoelectric phenomenon continuously. In the process, they can deform themselves without significantly altering the structure or design properties of the device in which they are operating (Wang et al., 2019). Direct actuators can be further divided into unimorph, bimorph, and amplified actuators. This subclassification refers to the energy management that occurs once the piezoelectric phenomenon is initiated. The typical structure of a bimorph piezoelectric actuator is a pair of layers of piezoelectric material bonded to a layer of support material. The actuator is usually attached to a holding structure, such as a clamp Fig. 3a. At the tip of the cantilever, a material of a certain weight is added, which acts as a seismic mass Fig. 3b and contributes to the movement of the actuator. Unimorph actuators, like the cantilever, have only one layer of piezoelectric material. However, their structure and operation are the same as the bimorph cantilever, as shown in Fig. 3c. These actuators can be divided according to shape: square/rectangular, ring, circular, and cantilever types. They can also be divided according to the working mode: bending mode and linear expansion/ retraction mode. The transversal mode is the leading piezo coupling coefficient in the adopted operating methods (Zhou et al., 2024).

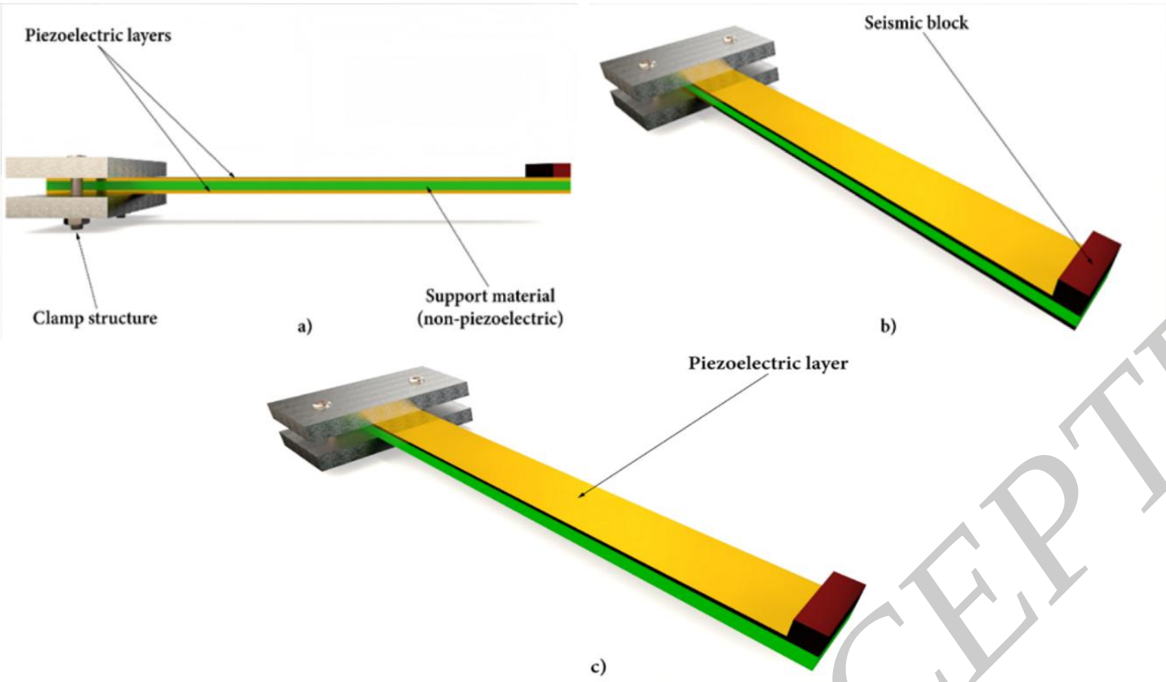

Figure 3: a) Bimorph piezoelectric cantilever. b) Seismic block on bimorph cantilever. c) Unimorph cantilever (Morales-Almanza et al., 2023).

The deformation of piezoelectrics due to a potential difference can be exploited to amplify this deformation and produce a displacement with more degrees of freedom in some situations required in complex structures (Spanner & Koc, 2016). Hence, the name is indirect because such actuators use the deformation motion (indirectly) already caused by the piezoelectric effect to amplify or complement that motion. (Zhang et al., 2012).

Another way to classify piezoelectric devices is by their materials, whose generation can be synthetic or natural, and from these two distributions, it is possible to divide the wide range of these materials, as shown in Table 1.

Table 1: General classification of piezoelectrics based on materials (Mishra et al., 2019).

Synthetic (Herper, 1992)				Natural (Jaffe et al., 1971)
Lead-Free (Waqar et al., 2022)	Lead-Based (Li, 2024)	Polymers (Smith & Kar-Narayan, 2022; Yue et al., 2022)	Composites (Mokhtari et al., 2021)	
Zinc Oxide [2,4]	Lead Zirconate Titanate [2,3]	Polyamide	PZT: PVDF	Quartz [1,4]
Aluminium Nitride		Polyvinylidene Fluoride	PZT: PDMS	Rochelle Salt
Barium Titanate [2,3]		Polylactic Acid	PZT: ZnO	Topaz
Lithium Tantalate [1]		Carbon Nanotubes	Cellulose: Barium Titanate	Tourmaline
Lithium Niobate [1]		Cellulose		
Potassium Niobate [3]		Naffion		
Sodium Niobate				

[1]Monocrystalline [2]Polycrystalline [3]Ferroelectric [4]Non-ferroelectric.

As various paths emerge in biomedical technologies using piezoelectrics, this work provides an overview of piezoelectric devices applied to the biomedical field. In addition, niche and declining topics were found using a bibliometric analysis. Bibliometric analysis allows for scoping the relevant topics regarding piezoelectrics in biomedical applications.

2. Methodology

A bibliometric analysis was performed to obtain state-of-the-art information about piezoelectric materials in the biomedical field (Aria & Cuccurullo, 2017). A search was performed using Scopus and Dimensions databases. The keywords employed for the search were “piezoelectric,” “biomedical,” and “application.” No other filters were included in the search to avoid bias. The trending topics were obtained using R software.

Since the searches were conducted without filters, the earliest papers date back to 1976. Figure 4 provides an updated perspective over the last decade; it should be noted that 3D printing, miniaturization, current generation, and tissue generation are emerging trends. In Figure 4, gray bars represent the time lapse in which the term appears, and the size of the circles represents the frequency of appearance of the term for the specific year.

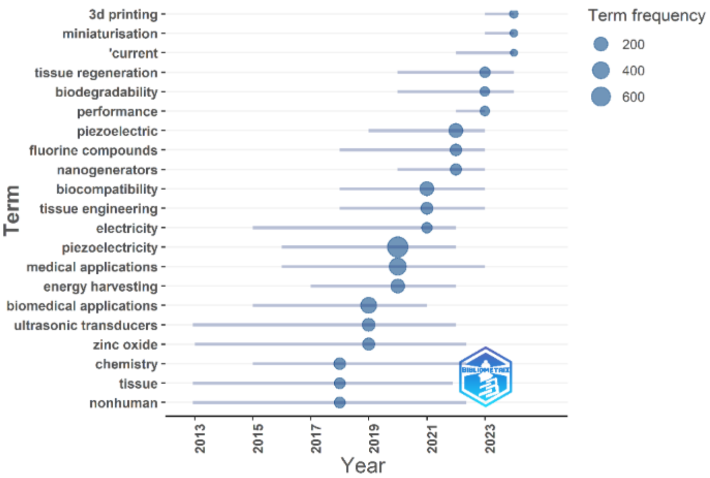

Figure 4: Frequency of occurrence of search-related terminology, updated search.

Figure 5 shows a thematic map that allows for visualizing the main research themes. The found topics are displayed based on their relevance and development degree, thus basic and emerging themes can be identified. As Figure 5 shows, the chemistry and tissue engineering terms are identified as the most relevant topics, whereas piezoelectric remains a basic term.

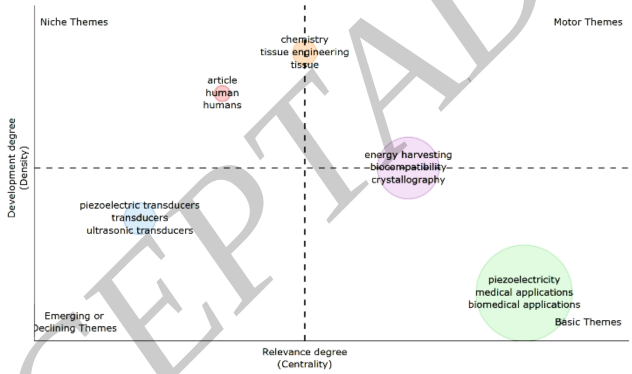

Figure 5: Relevance of search-related terminology, divided into niche categories.

3. Energy Harvesting

When alternative forms of energy generation are discussed, the first things that come to mind are wind, solar, and hydroelectric generation methods, as they are the most popular due to their widespread presence in the media and educational institutions. They are also where industrial sectors dedicated to their operation have been established. (Kieffer & López-Peña, 2016)

Although this method has considerable potential for power generation, its application in small, low-power devices is less common.

Among the lesser-known alternative energy sources are thermoelectric materials, which produce electrical energy from a thermal difference. The tribology effect is used to obtain high electrical potential with a very low current, hence generating in the nanowatt (nW) orders (Morales-Almanza et al., 2023). However, parallel to these conventional forms of electrical energy generation, there is "wasted" energy that can be captured and processed by using materials such as piezoelectrics, thermoelectrics, triboelectrics, and electromagnetics (Morales-Almanza et al., 2023) to be used as an energy source by rectifying, storing, and regulating the voltage (Morales-Almanza et al., 2023). It can be said that the energy generated can be used to sense physical phenomena, such as temperature and pressure. Although this is possible, Energy Harvesting only focuses on the pure and simple generation of energy, not using this as a signal processor (Alder & McCallum, 1983).

4. Applications

As mentioned, piezoelectrics are utilized in various health applications due to their high sensitivity and self-powered nature. The piezoelectric effect is valuable in pulse and respiration monitoring; artery pulses and chest movement are monitored using piezoelectrics, as Chen mentioned (Chen et al., 2017).

Similarly, changes in blood vessel diameter due to blood pressure can be monitored directly from in-site sensors using piezoelectrics; blood pressure monitoring is critical for patients with cardiovascular conditions. Wearable devices equipped with piezoelectric sensors can also continuously monitor blood pressure, which is crucial for patients with hypertension or other cardiovascular conditions (Rakici & Kim, 2024).

Gait Recognition: An array of flexible piezoelectric sensors can be used in gait recognition systems to monitor respiratory pulse and muscle behavior, aiding in physical therapy and rehabilitation (Zhang et al., 2023).

Vital Signs Detection: These sensors can detect vital signals such as breathing, heartbeats, and hand movements, which are particularly useful for monitoring patients post-stroke or with traumatic brain injuries (Purushothaman et al., 2023).

As a rehabilitation tool, bimorph piezoelectrics are used as sensors and monitoring devices to improve the movement and comfort of a limb prosthesis. If placed in the socket of a leg prosthesis in the section that is in direct contact with the residual limb, they can identify movement and rectify its direction in each stride by monitoring the pressure distribution in the regions of the leg where such pressure is expected, such as the inner, distal posterior, and posterior regions (Kieffer & López-Peña, 2016).

In oncology, specifically in cancer detection, photoacoustics can be used to focus on a specific area of interest by utilizing laser light of a specific wavelength, which generates a sound that is measured by piezoelectric sensors.

This results in better resolution and appreciation of details in the tissue compared to the ionizing radiation method (Horsley et al., 2007).

The idea behind the photoacoustic technique is to utilize the thermoelastic effect resulting from tissue light absorption. A light source (usually a laser) is pointed toward an area of interest; the tissue expansion resulting from the light absorption generates pressure waves that can be detected using an ultrasound transducer. The main advantage of this technique over classic ultrasound is that light has better spatial resolution because of the wavelength employed. Another advantage is that because the excitation source is light in the non-ionizing frequency, no side effects are probed, and the light power is respected (Lara Hernández & Flores Cuautle, 2023)

4.1. Echotomography

Echotomography is a three-dimensional extension of the two-dimensional ultrasound imaging systems. 3D images are constructed using a 2D image series on the condition of knowing each plane's position and orientation. Under normal conditions, 2D images are obtained using a 1D transducer array with a mechanical scanning system rotating or translating. The main drawback of the mentioned system is the time consumed by the mechanical system; this means the mechanical system's velocity limits the scanning time. Additionally, the obtained 3D image is not a real-time image.

Further improvement is the development of 2D transducer arrays. Thus, 3D images can be obtained by electrically switching the transducer rows, columns, or a combination. Using a 2D transducer array reduces the scanning time and, at the same time, reduces the movement artifacts.

In searching to improve ultrasound transducers' performance, several configurations and techniques have been developed for manufacturing transducers, such as stereolithographic transducer array (Chen et al., 2018), geodesic (Qiu et al., 2016), helical-like (Chen et al., 2019).

Healthcare devices are one type of biomedical engineering design proposed by Jiang and coworkers (Chen et al., 2019); reliability, mobility, and affordability are crucial parameters considered in the design. Then, healthcare devices devoted to monitoring biomedical variables must accomplish the aforementioned features.

One of the essential vital constants to be monitored is blood pressure; thus, Dagdeviren and collaborators (Dagdeviren et al., 2014) proposed a PZT-based piezoelectric arrangement designed for monitoring variations of the blood pressure in the near-surface arteries; this information is related to radial artery augmentation, providing information on possible arterial diseases. The piezoelectric arrangement proposed by Dagdeviren (Dagdeviren et al., 2014) is low-weight (2 mg) and low-size (~1 cm2, thickness 25 µm), proving to be an option for continuous wellness monitoring.

Another biomedical application is the pacemaker proposed by Hwang and colleagues (Hwang et al., 2014), which utilizes a PMN-PT piezoelectric as the energy source. A 1.7cm^2 plastic is a substrate for this single-crystal piezoelectric in this application. This device can charge the pacemaker battery in 3 hours using the heartbeat as an energy source. In this research, the authors demonstrate an energy production of 8.2 V at frequencies within the heartbeat range (0.3 Hz) (Hwang et al., 2014).

An acoustic wave generator device was developed by Zhu and coworkers (Zhu et al., 2020); this device can move medication to a specific site in the digestive tract using an endoscope. This transducer comprises piezoelectric crystal material, leading to less invasive digestive treatments. The device was able to generate excitation at 6.9 MHz, and the results shown by in vitro tests indicate that the device can penetrate medication into the small cavities of the gastrointestinal tract and is safe for use in the human body and other surgical applications.

The use of piezoelectric materials in biomedicine offers numerous advantages. Among these is their ability to convert mechanical energy into electrical energy and vice versa, making them useful in medical imaging, neural stimulation, and biomechanical force sensing applications. However, some general limitations and counter-productivity are also associated with these materials and their use. Some of these include:

- Biological compatibility: Some piezoelectric materials may not be biocompatible, which could trigger immune or inflammatory responses in the body (Tang et al., 2017).
- Degradation over time: Piezoelectric materials may experience degradation over time due to mechanical or chemical fatigue, which could reduce their effectiveness and durability in long-term biomedical applications (Tang et al., 2017).
- Toxicity: Some piezoelectric materials may contain toxic components that could damage biological tissues, and although the levels of damage may be very low, there is the possibility of an adverse reaction (Jarkov et al., 2022).
- Limited frequency response: Some piezoelectric materials have a limited frequency response, which may restrict their usefulness in applications requiring a wide range of frequencies, such as biological signal detection (Paganelli et al., 2010).
- Sensitivity to environmental conditions: Piezoelectric materials can be sensitive to environmental conditions, such as temperature and humidity, which could affect their performance in biomedical environments (Paganelli et al., 2010).
-Dimensions and handling: Due to their dimensions and mechanical properties, some piezoelectric materials can be challenging to handle or integrate into biomedical devices (Rafael, 2023).
- Cost: The fabrication of advanced piezoelectric materials can be expensive due to the precision machinery required, which could limit their adoption in large-scale biomedical applications (Kar et al., 2021).
-Fragility: Raw piezoelectric wafers are fragile and can easily crack when exposed to environmental factors or subjected to mechanical stress, limiting their durability and reliability (Comyn et al., 2021).
-Engineering Challenges: The engineering of piezoelectric materials to achieve specific properties, such as a higher piezoelectric response, stable domain structure, and hysteresis-free behavior, can present challenges (Gao et al., 2024).

These drawbacks highlight some of the limitations and challenges associated with the use of piezoelectric materials in various applications (Mohammadpourfazeli et al., 2023)

5. Prospectives

The use of piezoelectric materials in biomedicine has excellent potential and is expected to grow. Some of these projections include power generation, where piezoelectric materials could be utilized to produce energy from body movements or pulsations. Wearable electronic devices or temperature-sensitive materials can power implantable or portable medical devices without the need for batteries.

Piezoelectric transducers used as sensors can be employed as highly sensitive mechanisms to measure various biomedical parameters, including blood pressure, heart rate, and muscle activity. These devices could be smaller, more precise, and less invasive than current ones, allowing continuous and non-invasive health monitoring.

In terms of image processing, piezoelectric materials can be used in photoacoustic technologies, such as ultrasound, to improve image quality and spatial resolution. This could lead to more accurate and earlier diagnoses of diseases, and, as in the case of cancer, where one of the conventional screening methods is radiology, the use of piezoelectrics could avoid the use of ionizing radiation. Just as piezoelectrics can be used for diagnosing diseases, they can also be used for rehabilitation therapies. These devices can be integrated into neuromuscular or brain stimulation equipment to treat conditions such as Parkinson's disease, epilepsy, or depression. These devices could be more precise and selective in stimulating specific regions of the body or brain. Furthermore, in the case of tissues, piezoelectrics can develop scaffolds or three-dimensional structures that mimic the mechanical properties of biological tissues. These scaffolds could provide a more favorable environment for cell growth and tissue regeneration, which could have applications in regenerative medicine and tissue engineering.

In summary, advances in the use of piezoelectric materials in the biomedical field offer innovative solutions for diagnosing, treating, monitoring, and rehabilitating.

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